Alignment transition in a nematic liquid crystal due to field-induced breaking of anchoring

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Abstract

We report on the alignment transition of a nematic liquid crystal from initially homeotropic to quasi-planar due to field-induced anchoring breaking. The initial homeotropic alignment is achieved by Langmuir-Blodgett monolayers. In this geometry the anchoring strength can be evaluated by the Frederiks transition technique. Applying an electric field above a certain threshold provokes turbulent states denoted DSM1 and DSM2. While DSM1 does not affect the anchoring, DSM2 breaks the coupling between the surface and the liquid crystal: switching off the field from a DSM2 state does not immediately restore the homeotropic alignment. Instead, we obtain a quasi-planar metastable alignment. The cell thickness dependence for the transition is related to the cell thickness dependence of the anchoring strength.

Nematic liquid crystals (NLCs) can be aligned along a well defined direction either by treating the confining surface in a certain way [1], or by applying an external electric (or magnetic) field [2]. In the absence of an external field the director $\mathbf{n}$ coincides with the so-called "easy axis" whose orientation depends on the surface treatment. An additional electric (or magnetic) field can, depending on the LC's dielectric (magnetic) anisotropy, destabilize this orientation and the director $\mathbf{n}$ will deviate from the easy axis (Frederiks transition). Depending on the strength of that field, the anchoring is said to be weak or strong.

At higher fields, above certain thresholds, modulated structures due to convective instabilities appear which are characterized by a periodic distortion of the nematic director $\mathbf{n}$ along certain directions and which can be visualized in form of regular

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patterns. At still higher electric fields one finds a second and a third threshold that correspond to the appearance of two different turbulent states called DSM1 and DSM2, where DSM stands for "dynamic scattering mode" because the director **n** undergoes a chaotic motion which leads to intense scattering of light.

These instabilities have been extensively studied for planar and homeotropically oriented MBBA, which is a NLC with negative dielectric anisotropy. We have found particularly interesting and helpful for our present study the work of Versace *et al.* [3–5] who have investigated the transition between DSM1 and DSM2 states and suggested that this transition may be related to a breaking of the surface anchoring. We note, however, that their experiments have been performed in planar MBBA cells of fixed thickness.

In this work we present a detailed experimental study on the effects of the turbulent states on the homeotropic nematic anchoring and present direct evidence of field-induced breaking of the anchoring. The use of homeotropically aligned MBBA cells has the important advantage that in this geometry one can obtain the independent information about the surface anchoring strength from the Frederiks transition threshold. This is not possible in planar MBBA cells as the electric field stabilizes the alignment in this case.

Recently we have shown [6,7] that a Langmuir-Blodgett (LB) monolayer of stearic acid (C18) can be used to obtain a very good and stable homeotropic alignment of MBBA. LB monolayers of C18 have been deposited on ITO coated glass plates which have then been used to make sandwich cells of 4, 8, 10, and $15 \, \mu$m thickness. The samples were observed in a polarising microscope which was connected to an image acquisition system. A sinusoidal electric field was applied across the cells, perpendicular to the glass plates, and the optical response was monitored on the oscilloscope via a photodetector. We defined as threshold field the one at which $10 \, \%$ of the saturated value of the transmitted light intensity was reached. All investigations have been performed at room temperature.

At relatively weak electric fields the Frederiks transition takes place. Since MBBA has negative dielectric anisotropy ($\Delta\varepsilon = -0.7$ [2]) the molecules want to orient perpendicular to the electric field, which is in conflict with the initial homeotropic alignment. The threshold field was found to be frequency independent [8].

From the electric field threshold it is possible to calculate [9] the anchoring strength w of the NLC on the surface according to the equation:

$$w = qK_3 \tan\left(\frac{qd}{2}\right), \quad \text{with} \quad q = E\sqrt{\frac{|\Delta\varepsilon|\varepsilon_0}{K_3}},$$

where d is the cell thickness, $\Delta\varepsilon$ is the dielectric anisotropy, ε_0 is the vacuum dielectric constant, K_3 is the bend elastic constant, and E is the electric field threshold at which the Frederiks transition takes place.

The anchoring strength was found to depend on the cell thickness. The values are shown in Figure 1. According to Barbero *et al.* [10,11] the thickness dependence of
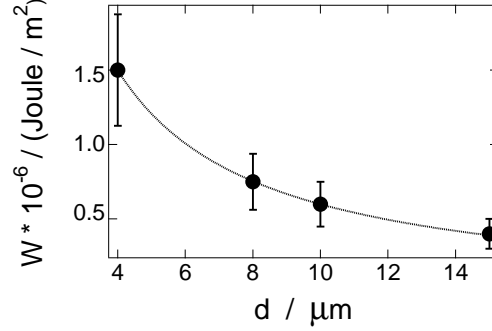
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Figure 1: Dots: anchoring strength of MBBA on LB monolayers of C18 as a function of the cell thickness. Dashed line: fit of the experimental values to the function in eqn. 1. The parameters of the best fit are: $w_R = 1.25 \times 10^{-5}$ Joule/m^2 and $\Sigma = 1.3 \times 10^{-4}$ C/m^2.

the effective anchoring strength is related to the presence of the conductive charges in the NLC volume and to the adsorption of charges at the boundaries. The actual distribution of charges in the external electric field depends on the cell thickness and due to the flexoelectric properties of NLCs the effective anchoring energy also appears to be thickness dependent. The effective anchoring strength can be written as:

$$w_{eff} = w_R + \frac{\sigma}{\varepsilon \varepsilon_0} \left[\frac{\Delta \varepsilon}{2\varepsilon} \lambda_D \sigma + 2e \right],$$ (1)

where w_R is the anchoring strength in the Rapini-Papoular [9] model, ε is the average dielectric constant ($\varepsilon = 5.05$ [2]), λ_D is the Debye screening length ($\lambda_D = 200$ nm [12]), e is the average flexoelectric coefficient ($e = -1.3 \times 10^{-12}$ C m^{-1} [13]), and

$$\sigma = \Sigma \frac{d}{d + 2\lambda_D}$$

is the absorbed charge density at the boundary, where Σ depends on the conductivity of the LC and on the characteristics of the surfaces. We have fitted the data in Figure 1 to the eqn. (1) and found that w_R is positive as it should be for an initially homeotropically oriented NLC [9].

Just above the Frederiks transition threshold the NLC is essentially quasi-planar oriented. On increasing the field above the Frederiks transition threshold we observed first modulated structures (Williams rolls), then their destabilization, and then the transition to the weakly turbulent state DSM1 (for more details about electrohydrodynamic instabilities in NLCs see for instance [13], chapter 5). Switching off the electric field from these states the homeotropic alignment is immediately restored. Increasing the electric field further above the DSM1 threshold, we observed the transition to the second turbulent state, DSM2. Domains of DSM2 nucleate at some points in the ne-
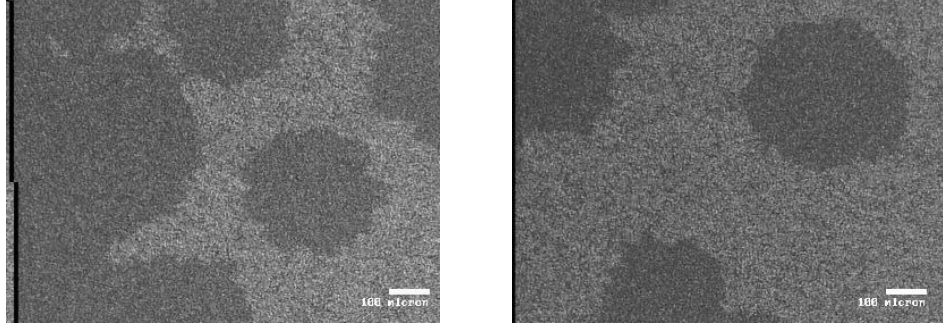
Figure 2: DSM2 domains expand in the DSM1 turbulent state. Note the circular form of the DSM2 domains which is due to the absence of a preferred direction in the plane of the cell given by the initial homeotropic alignment.

matic layer, which is in the DSM1 state, and expand to the whole sample (see Figure 2).

We would like to point out that the electric field was increased very slowly, so that the Frederiks transition as well as the modulate structures and the turbulences could fully develop.

DSM1 and DSM2 have different optical appearance: in both states the light is scattered very strongly, but in DSM2 the size of the scattering centers is much smaller than in DSM1, and DSM2 domains are darker than DSM1 domains between crossed polarizers. We note that in the case of planar MBBA, the DSM2 domains expand more quickly in the aligning direction [3]. In our case they expand in all directions with the same speed because the initial homeotropic alignment does not create a preferred direction in the plane of the cell. Hence, the domains are circular.

Switching off the electric field from the DSM2 state does not restore immediately the homeotropic alignment. Instead, the sample contains many defects (see Figure 3) that disappear rather quickly and leave the NLC in a metastable quasi-planar state. In other words, DSM2 causes a breaking of the anchoring of the NLC to the surface resulting in an alignment transition from homeotropic to quasi-planar.

The electric field thresholds for the onset of the DSM2 state are shown in Figure 4 for both the conductive and the dielectric regime [13, 14]. From Figure 4 one can readily see that the threshold field for DSM2 depends on the cell thickness, such that the threshold is higher in thinner cells. This cell thickness dependence of E_{DSM2} can be directly related to the cell thickness dependence of the anchoring strength. That is, if the anchoring strength decreases with d, a lower threshold will be needed to break the anchoring in thicker cells, which is indeed what we observe.

In the quasi-planar state in which the sample is left after switching off the electric field the NLC molecules are oriented in the direction of the NLC flow during the cell filling, while the LB deposition direction does not play any role. As mentioned above,
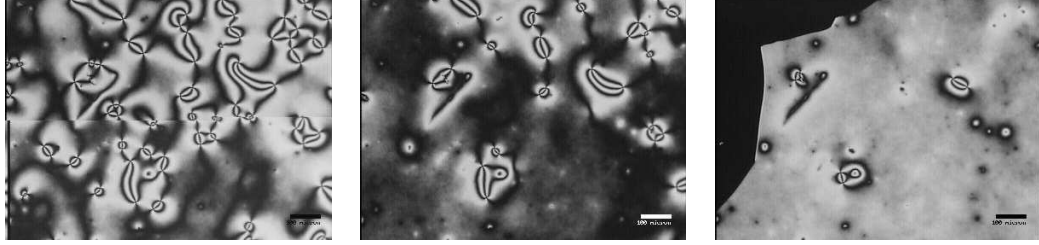
Figure 3: Evolution of alignment. Left: t=0; the electric field has been switched off and the sample does not return to the homeotropic alignment; instead, a metastable state appears which presents many defects. Center: t=10 s; the defects disappear and leave the sample in a quasi-planar state. Right: t=30 s; the defects have almost disappeared and the NLC adopts a planar alignment with the director oriented along the filling direction; the dark domain is a homeotropic domain which expands into the quasi-planar one until the whole sample becomes homeotropic again. Cell thickness $4\,\mu$m.
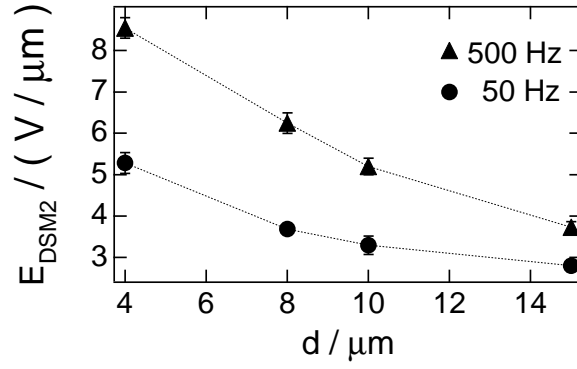

Figure 4: Electric field thresholds for the appearance of the DSM2 turbulent state as a function the cell thickness in the conductive regime ($f = 50\,$Hz) and in the dielectric regime ($f = 500\,$Hz).

the quasi-planar state is metastable: domains of homeotropic orientation nucleate with time at the edges of the cell or in the proximity of impurities and expand until the whole sample becomes homeotropic again [6].

Conclusions – We have studied an electric field induced alignment transition due to the breaking of the surface anchoring in initially homeotropic NLCs. In this context it was important to determine the anchoring strength within the same set of experiments as the electric field thresholds for the turbulent state DSM2 which is responsible for the breaking of the anchoring. The initial homeotropic alignment made it possible to study the two phenomena independently, which could not have been done in [3–5] because of the initial planar alignment of the NLC in that case.

The DSM1-to-DSM2 transition is affected by the surface anchoring. Versace *et al.* [3] have assumed that the DSM1-to-DSM2 transition is governed by a surface tilting transition induced by the external electric field: below the DSM1 threshold the nematic director deformation is confined to a plane; at the DSM1 transition point the director goes out of the plane, but this three-dimensional deformation reaches the surface only above the threshold of the DSM2 state, leading to anchoring breaking. This explanation is in agreement with our experimental results which show that the system does not immediately return to the initial homeotropic state after switching off the field in the DSM2 state. On the other hand, the DSM1 turbulent state does not affect the anchoring. Moreover, the cell thickness dependence of the electric field threshold for DSM2 follows the behavior of the cell thickness dependence of the anchoring strength, which is again a direct evidence of anchoring breaking.

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[14] Electrohydrodynamic instabilities (EHIs) are very sensitive to the frequency of the applied field [13]. We can distinguish two different threshold behaviors. For frequencies f less than a certain critical frequency f_c the threshold electric field E_W for the appearance of the EHIs increases sharply with f (conductive regime). For frequencies $f > f_c$ (dielectric regime) $E_W \propto \sqrt{f}$. We have measured the threshold electric fields for the appearance of the EHIs as a function of the frequency and estimated the critical frequency to be $f_c \approx 100\,\mathrm{Hz}$.